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Trust-based Human-Robot Collaboration (HRC) for High-Level Distributed Multi-Robot Motion Planning with Temporal Logic Constraints

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14. ABSTRACT
The research problem of this YIP grant is to synthesize symbolic motion plans (SMP) for multi-robot systems (MRS) with a human-in-the-loop through quantitative trust analysis. The objective is to develop scalable and adaptive multi-robot motion plans based on trust analysis for improved performance of the joint human-robot collaboration (HRC) systems. A dynamic, quantitative, and probabilistic human-to-robot trust model is developed by combining causal reasoning and direct evidence. This model also factors in the correlation among neighboring robots. Compositional reasoning approaches are developed to decompose the global task specification. An optimal multi-robot task allocation approach based on iterative automata decomposition has been developed. Our approach works with general task specifications and considers the task allocation problem with heterogeneous robots. Trust is used as a metric for specification decomposition and updated in a dynamic fashion. A trust-based runtime monitoring and switching mechanism is proposed for tradeoffs between task safety and efficiency. Deadlock- and livelock-free algorithms are designed to guarantee reachability of goals with a human-in-the-loop. Both ROS Gazebo and Matalab simulations are utilized for robot symbolic motion planning with a human-in-the-loop.

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1 Research Problem

The research problem of this YIP grant is to synthesize symbolic motion plans (SMP) for multi-robot systems (MRS) with a human-in-the-loop through quantitative trust analysis, which traditionally is very computationally expensive and hard to quantify. The objective is to develop scalable and adaptive multi-robot motion plans based on trust analysis for improved performance of the joint human-robot collaboration (HRC) systems. We seek to accomplish three interweaving research thrusts. Thrust I focuses on the estimation and modeling of human trust in robot for real-time robotic operations, especially in MRS. Thrust II develops trust-based distributed robot motion planning based on compositional reasoning so as to provide scalable solutions for multiple human-robot teaming. Thrust III seeks to synthesize trust-triggered real-time switches between manual and autonomous robot motion planning for tradeoffs between task efficiency and safety. We focus on the model, analysis, and implementation of effective HRI, which remains largely an open problem with current methods barely providing performance guarantees. Our primary focus on intelligence, surveillance and reconnaissance (ISR) missions is of high priority to the Air Force and DoD.

2 Method and Approach

A dynamic, quantitative, and probabilistic human-to-robot trust model is developed based on the time series trust model developed by Lee and Moray [1992] and the Online Probabilistic Trust Inference Model (OPTIMo) trust model developed by Xu and Dudek [2015]. Thus, we combine causal reasoning of updates to the robot's trustworthiness given its task performance with evidence from direct experiences to describe a human's actual amount of trust in each individual robot. We further extend this model to estimate the dynamic evolution of human trust in MRS factoring in the correlation among neighboring robots. Compositional reasoning approaches are developed to decompose the global task specification. An optimal multi-robot task allocation approach based on iterative automata decomposition has been developed. Our approach works with general task specifications and considers the task allocation problem with heterogeneous robots. Trust is used as a metric for specification decomposition and updated in a dynamic fashion. A trust-based runtime monitoring and switching mechanism is proposed for tradeoffs between task safety and efficiency. Since high-level manual planning is beneficial in certain circumstances but difficult to verify, the switching scheme is developed to choose between manual and autonomous robot motion planning. A runtime monitor as well as a checker is designed to track the actual trajectory of the robot under advanced manual motion planning. If any violation is detected, the advanced manual motion planning will be taken over by the baseline autonomous motion planning for guaranteed task safety and correctness. Atomic propositions for observation, communication, and control are proposed to address inter-robot collision avoidance. Deadlock- and livelock-free algorithms are designed to guarantee reachability of goals with a human-in-the-loop. Bisimular low-level continuous control laws have been developed for the unicycle model and quadrotor model to accomplish the tasks in a manner that the high-level discrete motion plans are preserved. Both ROS Gazebo and Matalab simulations are utilized for robot symbolic motion planning with a human-in-the-loop.

Direct human input and trust evaluation are provided demonstrating the successful implementation of the trust-based multi-robot symbolic motion planning methods.

2.1 Research Achievements and Scientific Discoveries

2.1.1 Human-Multi-Robot Trust Model

We developed a probabilistic trust inference model for quantifying the degree of trust that a human supervisor has in multiple (semi-) autonomous robots. Represented as a Dynamic Bayesian Network (DBN), our trust model infers beliefs over the human's moment-to-moment latent trust states, based on the history of observed interaction experiences. A separate model instance is trained on each user's experiences, leading to an interpretable and personalized characterization of that operator's behaviors and attitudes. Using data-sets being collected through an interaction study, we empirically assess out trust model under a broad range of configurations. These evaluation results highlight the trust model advances in both prediction accuracy and responsiveness. This near real-time human-robot trust estimate will enable the development of autonomous robots that can adapt their behaviors dynamically.

We first explored dominant aspects of trust applicable to HRC, and in particular to asymmetric teams. We focused on asymmetric, supervisor-worker style human-robots teams, in which a team of heterogeneous autonomous robots "worker" are responsible for handling assigned navigation tasks. In this model, the human "supervisor" has the ability to intervene and take over control of one/more robot(s) individually/simultaneously at different time scales, but should only do so when necessary, e.g., to correct the robot's mistakes, assign shorter/safer paths, or to switch to a new task objective. The human's interventions are assumed to always take precedence over the robot's autonomous controller while not jeopardizing the system safety. Our work focuses on visual and sensory navigation contexts, where a group of ground and/or aerial robots are autonomously driven by adaptive SMP. These robots can learn to follow different motion planning tasks such as exploring an area, reaching point(s) of interest, or patrolling between multiple points, etc., while avoiding obstacles on their ways. We investigate scenarios where an operator supervises a team of collaborative/competitive mobile robots, and model the evolution of human's trust in the robots' abilities to reliably follow the designated planning tasks.

We now present the trust model for asymmetric human-robots teams. This model treats the degree of human-robots trust T_t at each time step t as a random variable, and maintains belief distributions for these performance-centric trust measures, based on various factors of the interaction experience. This probabilistic representation is useful for inferring the human's expected trust state at a given time, as well as the amount of uncertainty of each such estimate. Figure 1 depicts an example of our trust model represented as a DBN for 3 robots. This recursive structure can be expanded for any number of agents. This probabilistic model encodes both causal and evidential relationships between trust, each robot's performance measures, and interaction factors, as well as evolution of trust states over time. In order to personalize the trust model to a particular user's behaviors and trust tendencies, we use the hard-assignment Expectation Maximization (EM) algorithm to find optimized model parameters given a training set of interaction experiences. Hard-assignment EM jointly optimizes the observational likelihood of all interaction data and the most likely sequence of latent trust states. In addition to inferring trust beliefs, this model can also be used to predict the probability distributions for the observed factors, e.g. human interventions.

2.2 Multi-robot SMP with a Human-in-the-loop

Robot SMP synchronizes task specifications with transition systems of robots to provide solutions to high-level goals in a discretized workspace. By incorporating high-level goals (e.g. correctness, safety) into temporal logic or automaton specifications, SMP can represent complex temporal task requirements and generate paths in the workspace with model checking techniques.

One of the challenges in SMP is the development of computationally efficient frameworks enabling provably correct solutions accommodating robot constraints and environment complexity, especially for multi-robot systems (MRS). We developed an automatic task allocation framework for MRS to deal with this problem based on automaton parallel decomposition techniques. It first synthesized a global task automaton by integrating a set of task specifications in Linear temporal logic (LTL) and regular expression (RE) to

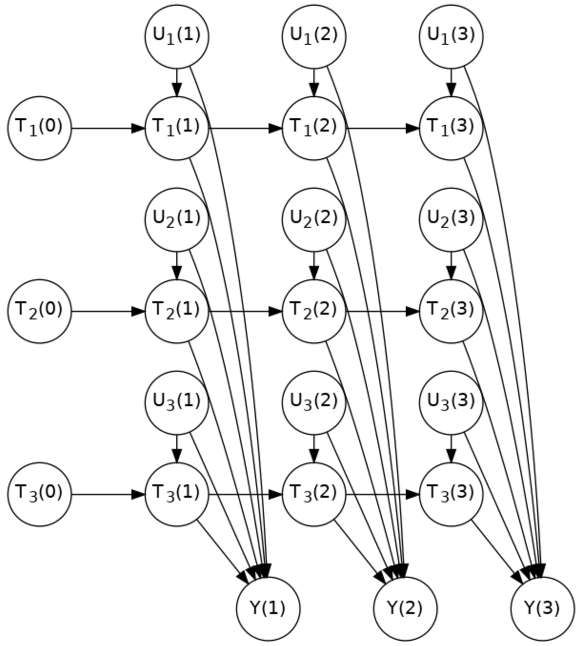

Figure 1: Unrolled dynamic Bayesian structure of the probabilistic trust inference model for a system with three robots.

describe the tasks for an MRS. Then, it developed an iterative parallel decomposition framework by projecting this automaton into a set of parallel decomposable event sets; thus, decomposing this automaton into a set of smallest parallel subtask automata. An enhanced parallel decomposition strategy is also presented by extracting the strictly decomposable automaton from a more general task automaton. Then, a task allocation automaton is synthesized for each subtask automaton to determine the robot assignment to tasks in a consecutive way. A parallel task allocation automaton is obtained through parallel executions of all these subtask allocation automata. The parallel execution operation guarantees the completeness of the solution while reducing the search space. Finally, an optimal task allocation solution can be found from this parallel task allocation automaton by considering both concurrency and costs of multi-robot tasking. Discrete state associated motion planning is performed after the task allocation for each individual robot. Task redecomposition and reallocation can be triggered to update the optimal task allocation and SMP, when intermittent communications exist among neighboring robots. An automaton decomposition and task allocation package was developed based on above process with JAVA. Several examples are implemented with the package in a simulation to verify the viability of the strategy.

On the other hand, the construction of cost or reward of each robot action is also a challenge problem to deal with. For most of the time, the cost of an action is a single dimensional metric, such as distance, time, performance and so on. There is a limited amount of literature discussing compositional metrics associated cost or reward for robot decision-making. We developed a human-robot trust integrated task allocation and motion planning framework for MRS in performing a set of tasks concurrently. A set of task specifications in parallel are conjuncted with MRS to synthesize a task allocation automaton. Each transition of the task allocation automaton is associated with the total trust value of human in corresponding robots. Here, the human-robot trust model is constructed with a DBN by considering individual robot performance, safety coefficient, human cognitive workload and overall evaluation of task allocation. A task allocation path with maximum encoded human-robot trust can be searched based on the current trust value of each robot in the task allocation automaton. SMP is implemented for each robot after they obtain the sequence of actions. The task allocation path can be intermittently updated with this DBN based trust model. The overall strategy is demonstrated by a simulation to verify its viability.

We also addressed the MRS inter-collision avoidance problem in the discrete path planning level. We developed a Deadlock- and livelock-free algorithm to guarantee reachability of goals with a human-in-the-loop. A set of non-trivial multi-robot simulations with direct human input and trust evaluation are provided demonstrating the successful implementation of the trust-based multi-robot symbolic motion planning methods.

2.2.1 Trust-Based Runtime Verification for MRS With a Human-in-the-Loop

We proposed a trust-based Run-time Verification (RV) framework for deploying multiple quad-rotors with a human-in-the-loop. By bringing together approaches from RV, trust-based decision-making, human-robot interaction (HRI), and hybrid systems, we developed a unified framework that is capable of integrating human cognitive skills with autonomous capabilities of multi-robot systems to improve system performance and maximize the intuitiveness of the HRI. On top of the RV framework, we utilized a probabilistic trust inference model as the key component in forming the interaction between the human and the team of robots, designed to maintain the system performance. A violation avoidance controller is designed to account for the unexpected/unmodeled environment behaviors, e.g. collision with static/moving obstacles. We also used the automata theoretic approaches to generate motion plans for the quad-rotors working in a partially-known environment by automatic synthesis of controllers enforcing specifications given in temporal logic languages. Finally, we illustrated the effectiveness of this framework as well as its feasibility through a simulated case study.

3 Impact

In this project, we seek to address the problem of symbolic robot motion planning with a human-in-the-loop, which has not been well explored before. We developed a novel quantitative, probabilistic, and dynamic trust model for real-time multi-robot operations. We focused on the model, analysis, and implementation of effective HRI, which remains largely an open problem with current methods barely providing performance guarantees. Our primary focus on ISR missions is of high priority to the Air Force. The proposed protocols can also be extended to other civilian and military applications with multi-human multi-robot collaboration such as logistics supports, flight management, and emergency and disaster rescue.

4 List of Resulting Publication

1. D. A. Spencer, Y. Wang, and L. Humphrey, "Trust-Based Human-Robot Interaction for Multi-Robot Symbolic Motion Planning", *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Daejeon, Korea, 2016.

2. M. Mahani and Y. Wang, "Run-time Verification for Symbolic Robot Motion Planning with human-in-the-loop", *The ASME Dynamic Systems and Control Conference (DSCC)*, Minneapolis, USA, 2016.

3. Y. Wang, L. Humphrey, Z. Liao, and H. Zheng, "Trust-based Multi-Robot Symbolic Motion Planning with a Human-in-the-Loop", *ACM Transactions on Interactive Intelligent Systems (TiiS)*, Special Issue on Trust and Influence in Intelligent Human-Machine Interaction, 2018.

4. M. Mahani and Y. Wang, "Trust-Based Runtime Verification for Multi-Quadrotor Motion Planning with A Human-in-the-Loop", *ASME Dynamic Systems and Control Conference (DSCC)*, Atlanta, USA, 2018.

5. H. Zheng, Z. Liao and Y. Wang, "Human-Robot Trust Integrated Task Allocation and Symbolic Motion planning for Heterogeneous Multi-robot Systems", *ASME Dynamic Systems and Control Conference (DSCC)*, Atlanta, USA, 2018.

6. H. Zheng and Y. Wang, "A Distributed Framework for Dynamic Task Allocation of Multi-Robot Symbolic Motion Planning", *American Control Conference*, Philadelphia, USA, 2019.

7. H. Zheng, M. Mahani,Y. Wang, "Parallel Task and Motion Planning for Heterogeneous Multi-Robot Systems under Temporal Logic Constraints", *IEEE Transactions on Robotics*, in preparation.

8. M. Mahani, Y. Wang, "Online Probabilistic Trust Inference Model of Multi Robot Systems", *AIAA Journal of Guidance, Control, and Dynamics*, in preparation.

5 List of Media Coverage

- Yue "Sophie" Wang of Clemson University wins top research award, the NewStand, Clemson University, February 2016
- Clemson awarded research grants, Greenville Journal, March 2016
- Clemson shows off national award winners, Independent Mail, March 2016
- Five Clemson Professors win top awards for young researchers, GreenvilleOnline, March 2016
- Clemson research teams attract $2.2M, SC BIZ News, March 2016
- Research awards seen as milestone for Clemson University engineering and science, EurekAlert! The Global Source for Science News, March 2016
- Research featured on SC EPSCoR/IDeA Research Focus spotlight, June 2017
- Interviewed by Clemson University Science Cast (totally 9 videos in the series), August 2017

6 List of Invited Talks

- Y. Wang, Cooperative Control, Decision-Making, and Motion Planning for Human-Robot Collaboration Systems. NYU Tandon School of Engineering, New York University, New York, NY, July 2016, invited talk
- Y. Wang, Trust-Based Control, Decision-Making, and Scheduling for Human-Robot Collaboration Systems, Automotive Research Center (ARC) Seminar, University of Michigan, Ann Arbor, MI, September 2016, invited talk
- Y. Wang, Trust-based Control, Decision-Making, and Motion Planning for Human-Robot Collaboration Systems. University of Notre Dame, Notre Dame, IN, March 2017, invited talk
- Y. Wang, Invited panelist for IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) workshop on "Verification of autonomous systems", Vancouver, Canada, September 24, 2017
- Y. Wang, Trust-based Control, Decision-Making, and Motion Planning for Human-Robot Collaboration Systems, Michigan State University, Lansing, Michigan, November 2017
- Y. Wang, Trust-based Control, Decision-Making, and Motion Planning for Human-Robot Collaboration Systems, Georgia Tech, April 2018

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Anqi Xu and Gregory Dudek. Optimo: Online probabilistic trust inference model for asymmetric human-robot collaborations. In *Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction*, pages 221–228. ACM, 2015.